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Temperature Measurement in the Challenging Environment of the ISS UPA Distillation Assembly Using Wireless RFID Sensors

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Urine Processor Assembly (UPA)

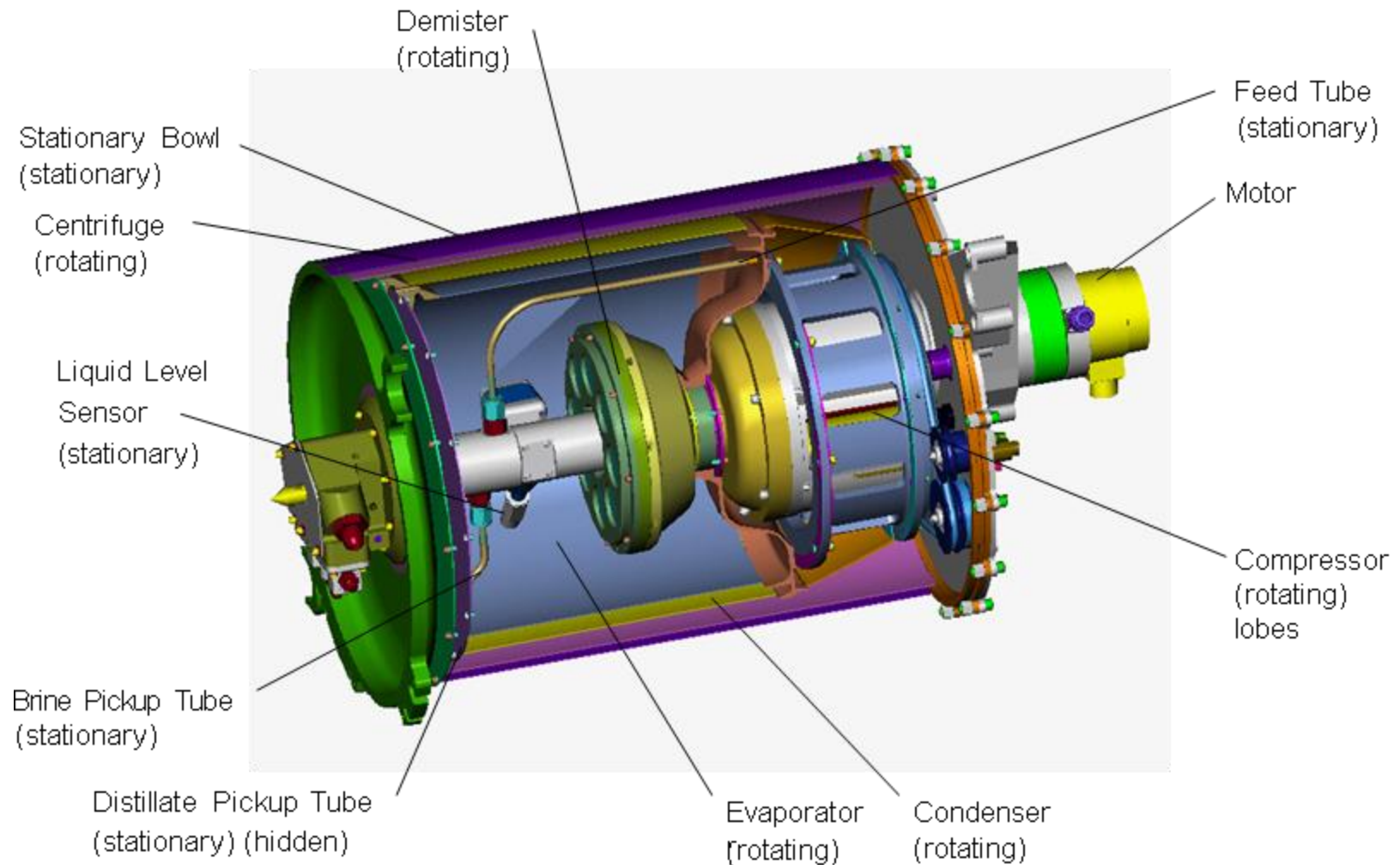


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- Installation of the UPA's Distillation Assembly (DA) on the International Space Station (ISS)
- Concentric spinning cylinders use centrifugal separation and vapor compression distillation to recover water from urine
- ES62 and EV34 are currently developing computational models of the UPA and its components
 - Will aid development of future exploration units
 - Need experimental measurements inside the system for correlation
 - Experiments are performed on ground test article, not ISS flight unit



Distillation Assembly Cross Section



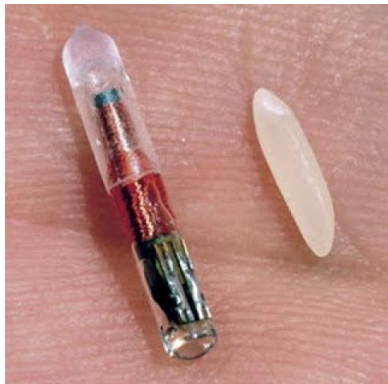
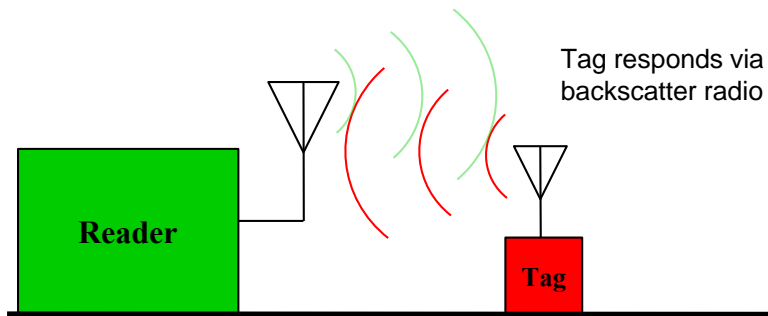
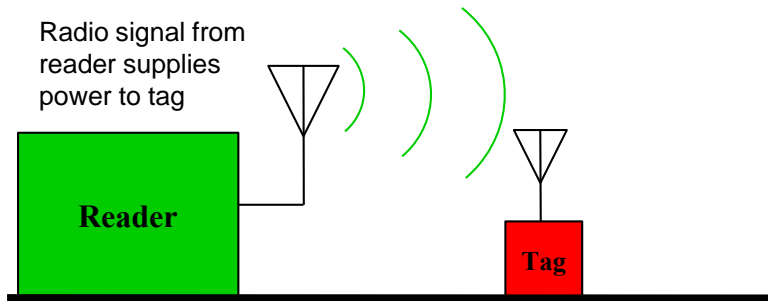


DA Measurement Challenges

- Rotating cylinders
 - Can't run wires to rotating parts
- Metal enclosure
 - Blocks radio waves
- Corrosive liquid
 - Blocks some EM radiation
 - Destroys many materials and adhesives
 - Shorts out electronics
- Complex to disassemble/assemble



Potential Solution: RFID Tags

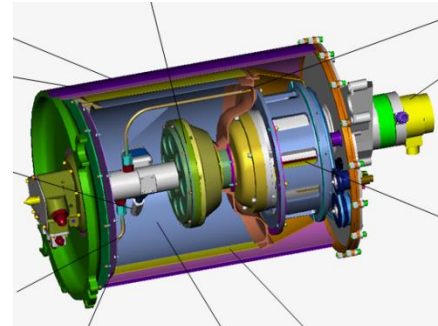
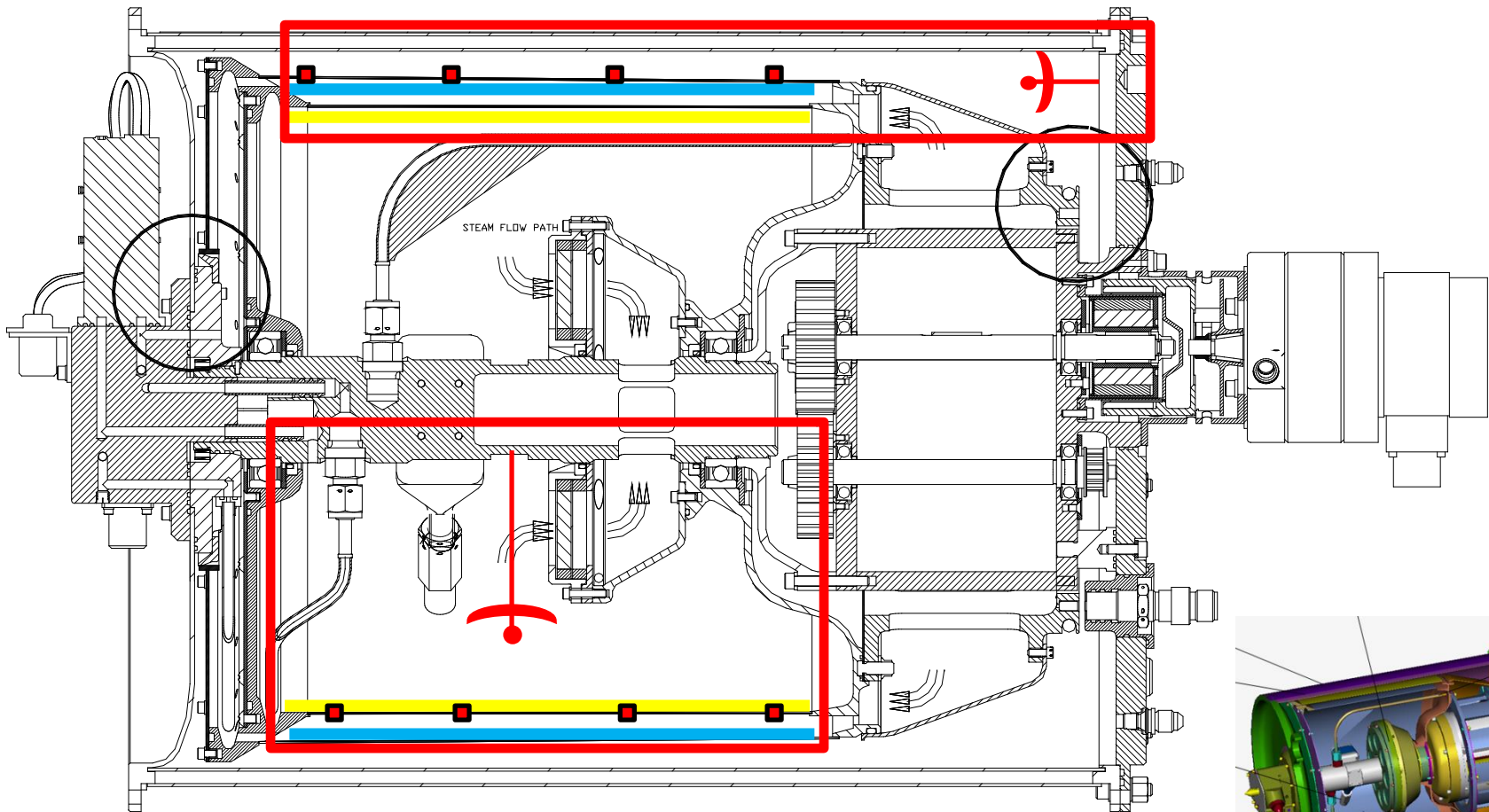


- Radio Frequency Identification
- Wireless
- “Passive” requires no battery
 - Powered by radio waves from the reader, senses and transmits information when actively read
- Compact
- Can be encapsulated for protection from harsh environments
- Can include various sensors
- Limitations
 - Short read range (a few feet)
 - Signal blocked by metal



RFID Implementation Concept

- Passive temperature sensors, antenna/readers wired to outside
- 2 antennas, 8 sensors: 4 inside evaporator, 4 outside condenser





First Phase: Feasibility Study

- Test & model RFID sensor performance in DA-like conditions
 - Sensors & reader inside metal cylinder
 - Sensors along narrow passage
 - Sensors immersed in pretreated urine
- Contractor
 - Phase IV Engineering
 - Specializes in custom RFID sensors
 - Performed tests and modeling for feasibility study



Feasibility Study Results: Outer Condenser Location

- Experimental sensor read tests in between aluminum cylinders with DA dimensions

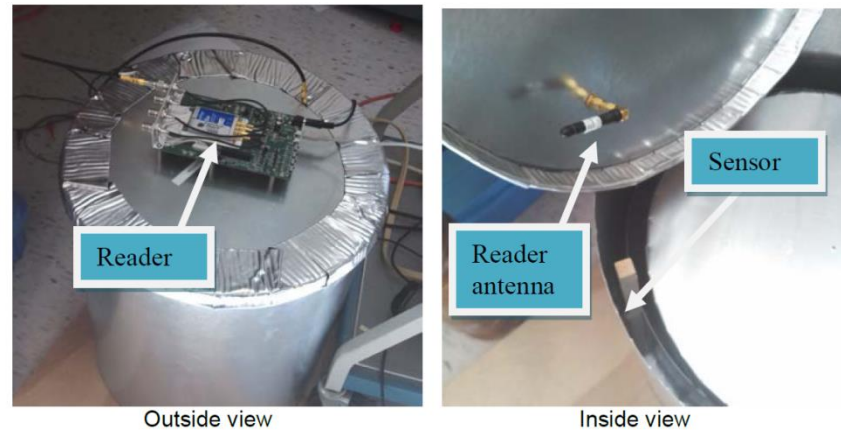


Image by Phase IV Engineering, Inc.

- Simulations of RF field strength in passage

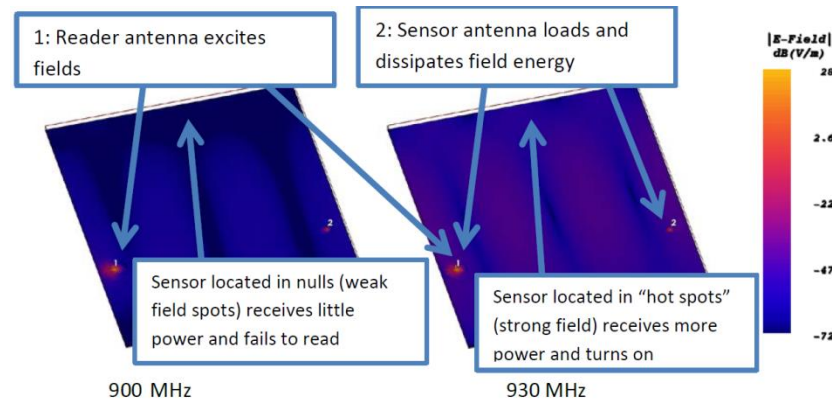


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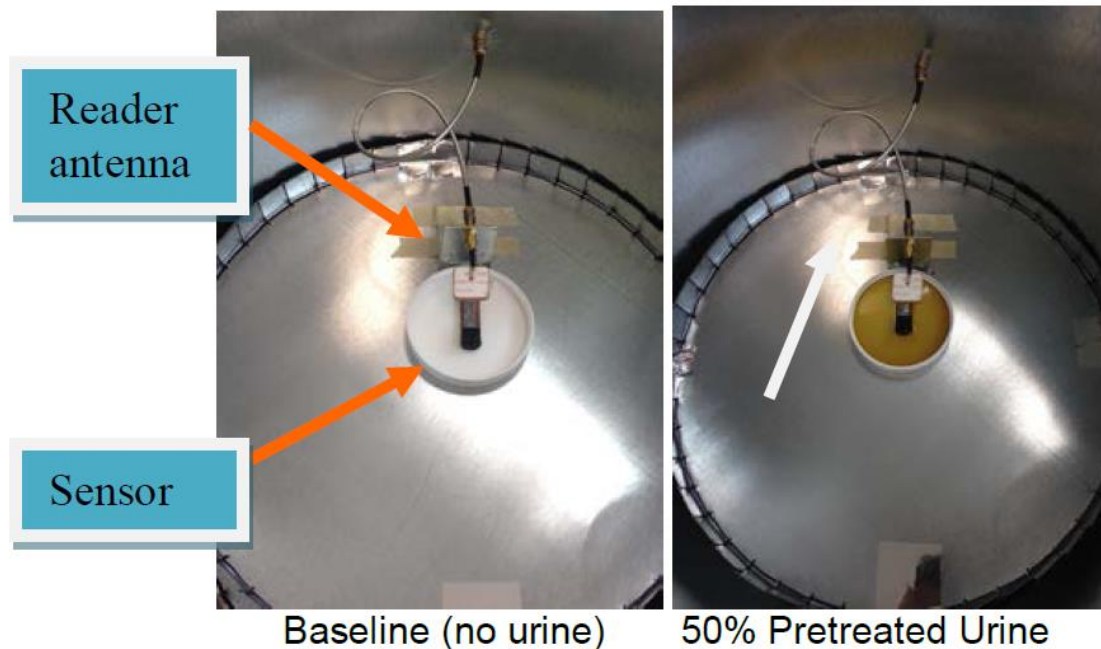
Figure 4. Electric field intensity in a plane cut $\frac{1}{4}$ " (midway through the $\frac{1}{2}$ " cavity) inside outer wall. As the system frequency changes and antennas reposition, the electric field intensity inside the outer wall changes.

- Tests show satisfactory field strength and read performance



Feasibility Study Results: Inner Evaporator Location

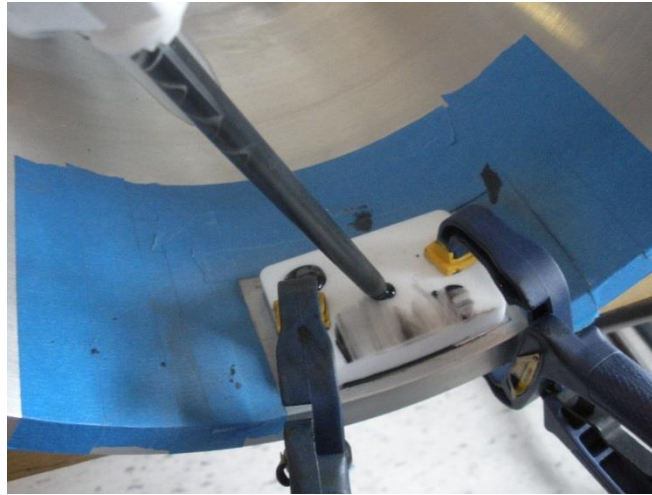
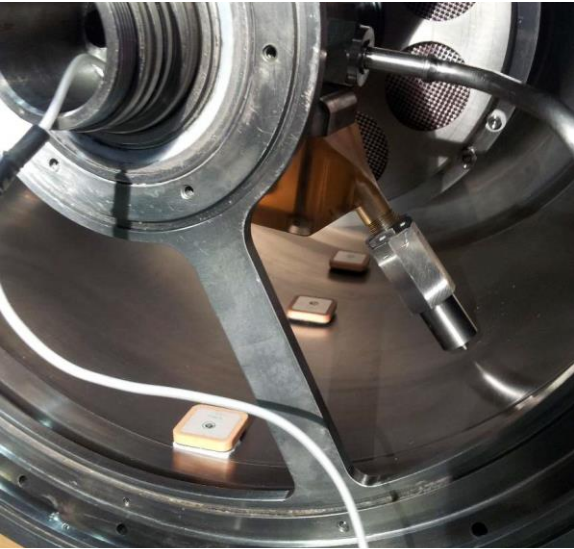
- Experimental tests of sensor reads while immersed in water and pretreated urine



- Tests show even a thin liquid layer completely blocks the signal
- Possible workaround: custom sensor with antenna raised above liquid level**
- Energy harvesting may also be an option



Installation



- Hardware developed and installed by Phase IV Engineering
- Tags encapsulated in Duralco 4525N epoxy (inside evaporator) and Silicone Nusil EPM-2410 (outside condenser)
 - Curved to fit wall and steer fluid around the sensor
- Installation completed Oct. 2014



Photos by Phase IV Engineering, Inc.

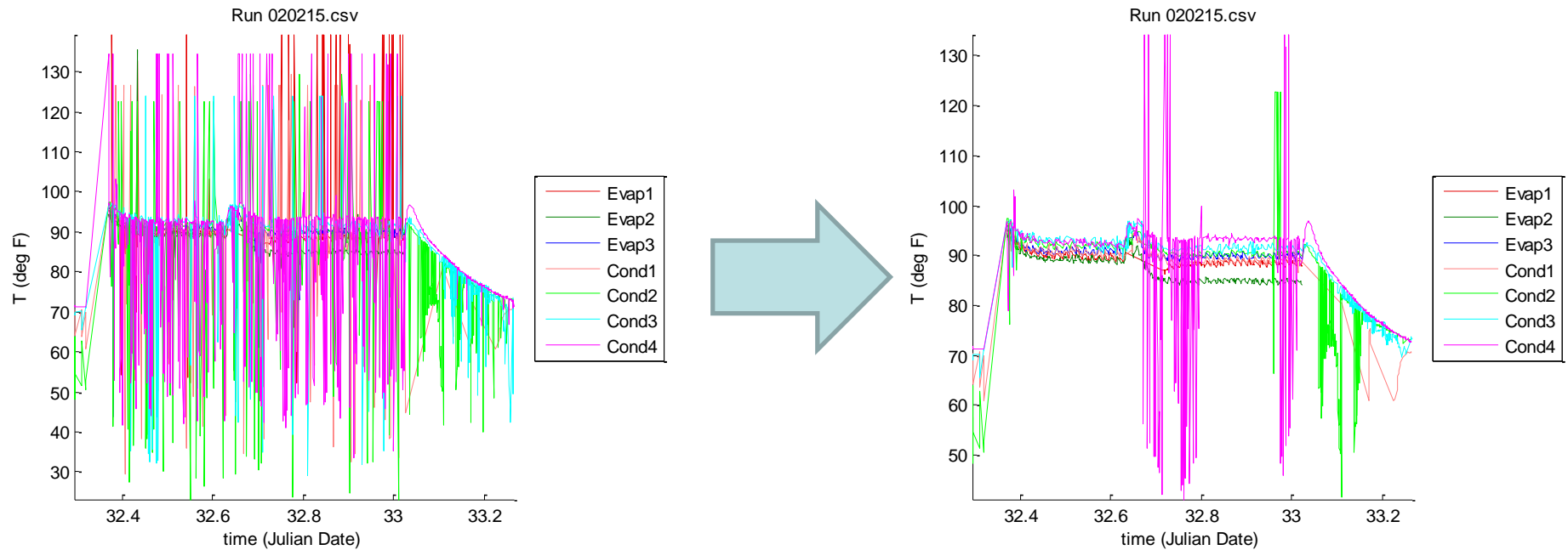


Preliminary Results

- Tested without fluid (dry) after installation Oct. 2014
 - Successful communication with all sensors in a dry system with spinning centrifuge
- Tested with wet system (nominal operation) early 2015
 - Confirmed communication with 7/8 sensors
 - Geometry affects performance
 - Better read rate for evaporator sensors in the center near antenna, lower rate for sensors at ends
 - Software tweaks may improve performance



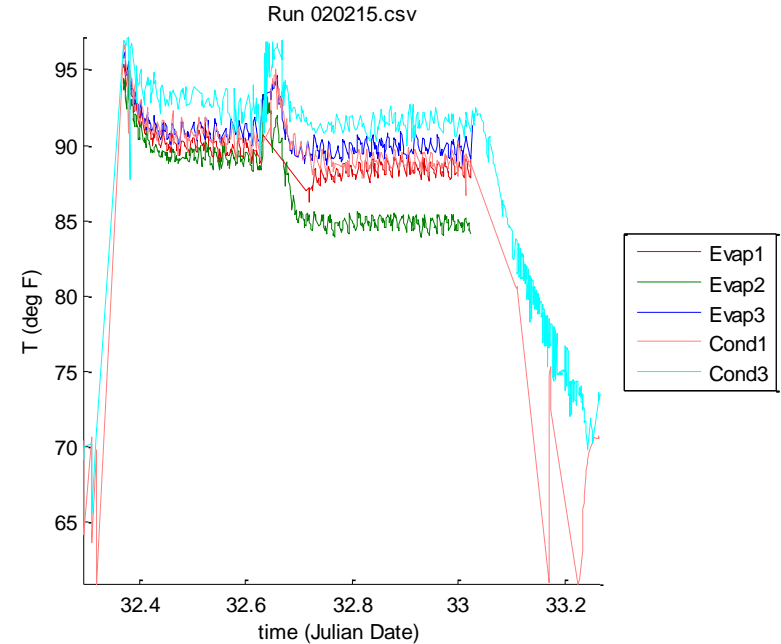
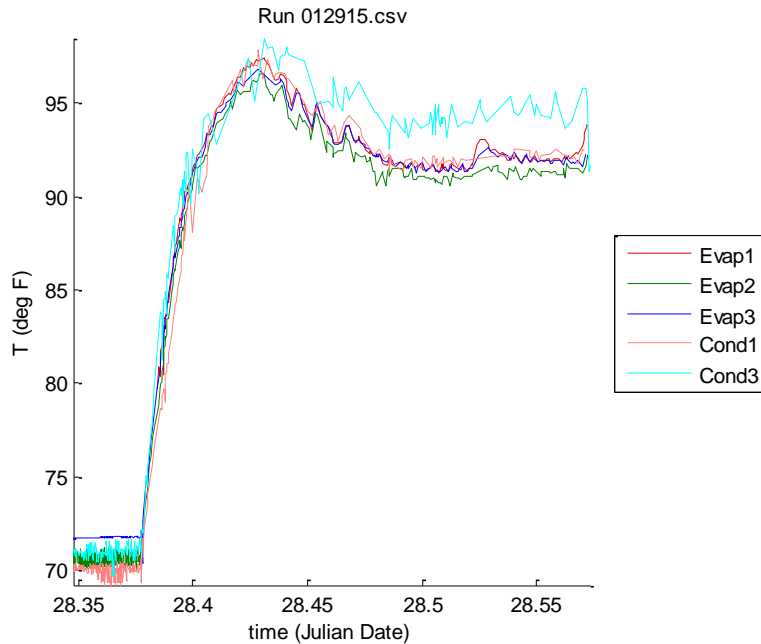
Wireless Data Analysis



- Many outliers in raw data
 - Demanding environment and read behavior
- Filtering
 - Can identify and remove outliers with moving statistics
 - Determine moving average and standard deviation within a window of data
 - Remove points that are outside a specified number of standard deviations from the mean (confidence interval)
 - Multiple filter passes remove more outliers
 - Different window sizes allow for fine vs coarse filtering
- Filter software is still evolving



Results and Findings



- Steady evaporator temperatures indicate stable phase change
- Temperature gradients
 - Highest temperatures near motor
 - Generally higher temperatures in condenser than evaporator
- All wireless sensors within ~4-7°F range
 - 2-5 degrees F for evaporator or condenser alone
 - **Quoted design for DA has condenser >10°F hotter than evaporator**
- Regular periodic fluctuation of ~1°F visible in all sensors
 - Also seen in DA thermocouples
 - Likely due to PCPA cycling



New Capabilities

- Temperature measurement in sealed, spinning centrifuge filled with caustic fluid
- Determine actual boiling/condensation temperatures
- Observe transient behavior
 - Startup/shutdown effects
 - Stable phase change
 - Response to disturbances



Problems & Issues

- **Noise**
 - Partially filtered by reader, but many outliers remain
 - Affected by operating conditions
 - More outliers in condenser sensors (narrow passage) than evaporator sensors (liquid splashing)
 - Mitigated through post-processing
- **Read rate**
 - Actual readings per minute below target
 - Still sufficient for our work
 - Affected by operating conditions
- **Interference**
 - No issues at first
 - After several weeks, wireless sensor system caused interference with thermocouples elsewhere in the system
 - Likely related to adhesive failure in evaporator and subsequent damage to those sensors



Problems & Issues (2)

- Adhesive failure
 - After several weeks of nominal operation, 3/4 evaporator sensors detached from the wall and failed
 - Condenser sensors (silicone adhesive) remained attached
 - Possible causes
 - Chemical – harsh chemicals may have damaged adhesive
 - Mechanical – force of moving fluid may have pulled sensors off
 - Material – adhesive may not have bonded well to wall
 - Rapid development schedule left insufficient time for full material compatibility tests. Abbreviated tests were done instead.





Conclusions & Lessons Learned

- A wireless RFID-based sensor system was successfully developed and integrated into the Urine Processor Assembly ground test article.
- The sensors have provided the first-ever temperature measurements of the evaporator and condenser regions of the Distillation Assembly during operation.
- The sensors provide real-time data on transient behavior within the DA and insight into temperature gradients in the system. This will allow for better validation of computational models of the DA and UPA.
- Several drawbacks and issues with the RFID sensing system were identified, including noisy data, slower than expected read rates, and the potential for interference with other equipment.
- A method for post-process filtering using moving statistics was developed and implemented to reduce the amount of noise in the wireless data.
- The failure of one of the sensor adhesives shows the difficulty of ensuring material compatibility, and the importance of testing.



Future Work

- Additional UPA testing with RFID sensors
- Improve filter software
- New sensors for the evaporator
 - Use silicone adhesive and water rather than pretreated urine
- Suggested upgrades for future RFID sensors
 - Better real-time filtering
 - Improve design to withstand high g-forces
 - Improve signal strength and read/transmit speed



Backup Slides



System Specifications

- Components
 - 8 metal-mount RFID sensors
 - Thermistor-based temperature measurement
 - 2 patch antennas
 - 1 reader
 - Operating software
- Sensor capabilities
 - Temperature ranges: 65-130°F, 100-200°F
 - Accuracy: $\pm 1^\circ\text{F}$
 - Read rate
 - Target: 6 reads/min
 - Actual (average): 0.5-2 reads/min
- System development cost: <\$100K



Distillation Assembly Overview

